PLASMA LAMP WITH DIELECTRIC WAVEGUIDE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation of U.S. application Ser. No. 09/809,718 ("'718") filed on Mar. 15, 2001, entitled "Plasma Lamp With Dielectric Waveguide," which claims priority to U.S. provisional application Ser. No. 60/222,028 filed on Jul. 31, 2000, entitled "Plasma Lamp." Applications 09/809,718 and 60/222,028 are hereby incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The field of the present invention relates to devices and methods for generating light, and more particularly to electrodeless plasma lamps.

[0004] 2. Related Art

[0005] Electrodeless plasma lamps provide point-like, bright, white light sources. Because they do not use electrodes, electrodeless plasma lamps often have longer useful lifetimes than other lamps. Electrodeless plasma lamps in the related art have certain common features. For example in U.S. Pat. Nos. 4,954,755 to Lynch et al., 4,975,625 to Lynch et al., 4,978,891 to Ury et al., 5,021,704 to Walter et al., 5,448,135 to Simpson, 5,594,303 to Simpson, 5,841,242 to Simpson et al., 5,910,710 to Simpson, and 6,031,333 to Simpson, the plasma lamps direct microwave energy into an air cavity, with the air cavity enclosing a bulb containing a mixture of substances that can ignite, form a plasma, and emit light.

[0006] The plasma lamps described in these references are intended to provide brighter light sources with longer life and more stable spectra than electrode lamps. However, for many applications, light sources that are brighter, smaller, less expensive, more reliable, and have long useful lifetimes are desired, but such light sources until now have been unavailable. Such applications include, for example, streetlights and emergency response vehicles. A need exists, therefore, for a very bright, durable light source at low cost.

[0007] In the related art, the air-filled cavity of an electrodeless plasma lamp typically is constructed in part by a metal mesh. Metal mesh is used because it contains the microwave energy within the cavity while at the same time permitting the maximum amount of visible light to escape. The microwave energy is typically generated by a magnetron or solid state electronics and is guided into the cavity through one or more waveguides. Once in the air-filled cavity, microwave energy of select frequencies resonates, where the actual frequencies that resonate depend upon the shape and size of the cavity. Although there is tolerance in the frequencies that may be used to power the lamps, in practice, the power sources are limited to microwave frequencies in the range of 1-10 GHz.

[0008] Because of the need to establish a resonance condition in the air-filled cavity, the cavity generally may not be smaller than one-half the wavelength of the microwave energy used to power the lamp. The air-filled cavity and thereby, the plasma lamp itself has a lower limit on its

size. However, for many applications, such as for high-resolution monitors, bright lamps, and projection TVs, these sizes remain prohibitively large. A need exists therefore for a plasma lamp that is not constrained to the minimum cavity sizes of the related art.

[0009] In the related art, a bulb typically is positioned at a point in the cavity where the electric field created by the microwave energy is at a maximum. The support structure for a bulb preferably is of a size and composition that does not interfere with the resonating microwaves, as any interference with the microwaves reduces the efficiency of the lamp. The bulbs, therefore, typically are made from quartz. Quartz bulbs, however, are prone to failure because the plasma temperature can be several thousand degrees centigrade, which can bring the quartz wall temperature to near 1000°C. Furthermore, quartz bulbs are unstable in terms of mechanical stability and optical and electrical properties over long periods. A need exists, therefore, for a light source that overcomes the above-described issues, but that is also stable in its spectral characteristics over long periods.

[0010] In plasma lamps of the related art, the bulb typically contains a noble gas combined with a light emitter, a second element or compound which typically comprises sulfur, selenium, a compound containing sulfur or selenium, or any one of a number of metal halides. Exposing the contents of the bulb to microwave energy of high intensity causes the noble gas to become a plasma. The free electrons within the plasma excite the light emitter within the bulb. When the

light emitter returns to a lower electron state, radiation is emitted. The spectrum of light emitted depends upon the characteristics of the light emitter within the bulb. Typically, the light emitter is chosen to cause emission of visible light.

[0011] Plasma lamps of the type described above frequently require high intensity microwaves to initially ignite the noble gas into plasma. However, over half of the energy used to generate and maintain the plasma typically is lost as heat, making heat dissipation a problem. Hot spots can form on the bulb causing spotting on the bulb and thereby reducing the efficiency of the lamp. Methods have been proposed to reduce the hot spots by rotating the lamp to better distribute the plasma within the lamp and by blowing constant streams of air at the lamp. These solutions, however, add structure to the lamp, thereby increasing size and cost. Therefore, a need exists for a plasma lamp that requires less energy to ignite and maintain the plasma, and includes a minimum amount of additional structure for efficient dissipation of heat.

BRIEF SUMMARY OF THE INVENTION

[0012] This invention provides distinct advantages over the electrodeless plasma lamps in the related art, such as brighter and spectrally more stable light, greater energy efficiency, smaller overall lamp sizes, and longer useful life spans. Rather than using a waveguide with an air-filled resonant cavity, embodiments of the invention use a waveguide having a body consisting essentially of at least one dielectric material having a dielectric constant greater than

approximately 2. Such dielectric materials include solid materials such as ceramics, and liquid materials such as silicone oil. A larger dielectric constant permits "dielectric waveguides" to be significantly smaller than waveguides of the related art, enabling their use in many applications where the smallest size achievable heretofore has made such use impossible or impractical.

[0013] In one aspect of the invention, a lamp includes a waveguide having a body comprising at least one dielectric material and having at least one surface determined by a waveguide outer surface. Each material has a dielectric constant greater than approximately 2. The lamp further includes a first microwave probe positioned within and in intimate contact with the body, adapted to couple microwave energy into the body from a microwave source having an output and an input and operating within a frequency range from about 0.5 to about 30 GHz at a preselected frequency and intensity. The probe is connected to the source output. The frequency and intensity and the body shape and dimensions are selected so that the body resonates in at least one resonant mode having at least one electric field maximum. The lamp further includes at least one lamp chamber depending, respectively, from at least one waveguide outer surface into the body, with each chamber at a location corresponding to an electric field maximum during operation. The lamp further includes a gas-fill in each chamber which when receiving microwave energy from the resonating body forms a light-emitting plasma.

[0014] In another aspect of the invention, a lamp includes a waveguide having a body with a main portion including a solid dielectric material and a body first side, and a protrusion extending from the first side and terminating in a second side determined by a waveguide outer surface from which depends a lamp chamber into the protrusion. The lamp further includes a microwave probe positioned within and in intimate contact with the body main portion, adapted to couple microwave energy into the main portion from a microwave source having an output and an input and operating within a frequency range from about 0.5 to about 30 GHz at a preselected frequency and intensity. The probe is connected to the source output. The frequency and intensity and the body main portion shape and dimensions are selected such that the main portion resonates in at least one resonant mode having at least one electric field maximum. The lamp further includes a bulb envelope substantially within the chamber, containing a gas-fill which when receiving microwave energy from the resonating body main portion forms a light-emitting plasma.

[0015] In still another aspect of the invention, a lamp includes a waveguide having a body including a solid dielectric material and a side determined by a waveguide outer surface from which depends a lamp chamber. The chamber aperture is circumscribed by a bulb envelope support sealed to the outer surface. The lamp further includes a microwave probe positioned within and in intimate contact with the body, adapted to couple microwave energy into the body from a microwave source having an output and an input and operating within a frequency range

from about 0.5 to about 30 GHz at a preselected frequency and intensity. The probe is connected to the source output. The frequency and intensity and the body shape and dimensions are selected such that the body resonates in at least one resonant mode having at least one electric field maximum. The lamp further includes a bulb envelope substantially within the chamber and hermetically sealed to the bulb envelope support. The bulb envelope contains a gas-fill which when receiving microwave energy from the resonating body main portion forms a light-emitting plasma.

[0016] In yet another aspect of the invention, a method for producing light includes the step of coupling microwave energy into a waveguide having a body including at least one dielectric material and having at least one surface determined by a waveguide outer surface from which depends at least one lamp chamber into the body. Each material has a dielectric constant greater than approximately 2. The energy frequency and intensity and the body shape and dimensions are selected such that the body resonates in a least one resonant mode having at least one electric field maximum. The method further includes the step of directing resonant microwave energy into the lamp chamber(s), with each lamp chamber containing a gas-fill including a plasma-forming gas and a light emitter. The method further includes the step of creating a plasma by interacting the resonant energy with the gas-fill, thereby causing emission of light.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] **FIG. 1** illustrates a sectional view of a dielectric waveguide integrated plasma lamp (DWIPL) including a waveguide having a body consisting essentially of a solid dielectric material, integrated with a bulb envelope containing a light-emitting plasma.

[0018] **FIGs. 2A** and **2B** illustrate sectional views of alternative embodiments of a DWIPL.

[0019] **FIGs. 3A** and **3B** illustrate a sectional view of an alternative embodiment of a DWIPL wherein the bulb envelope is thermally isolated from the dielectric waveguide.

[0020] **FIGs. 4A-D** illustrate different resonant modes within a rectangular prism-shaped dielectric waveguide.

[0021] **FIGs. 5A-C** illustrate different resonant modes within a cylindrical prism-shaped dielectric waveguide.

[0022] **FIG. 6** illustrates a DWIPL embodiment wherein a feedback mechanism provides information to a microwave source from a probe probing the waveguide field, thereby dynamically maintaining a resonant mode within the waveguide.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0023] Turning now to the drawings, **FIG. 1** illustrates a preferred embodiment of a dielectric waveguide integrated plasma lamp (DWIPL) **101**. DWIPL **101** includes a source **115** of microwave radiation, a waveguide **103** having a body **104** formed of a solid dielectric material, and a microwave probe **117** coupling the radiation source **115** to the waveguide **103**. Waveguide **103** is determined by opposed sides **103A, 103B,** and opposed sides **103C, 103D** generally transverse to sides **103A, 103B**. As used herein, the term "waveguide" generally refers to any device having a characteristic and purpose of at least partially confining electromagnetic energy. As used herein, the term "dielectric waveguide" refers to a waveguide having a body consisting essentially of at least one dielectric material having a dielectric constant greater than approximately 2. As used herein, the term "probe" is synonymous with "feed" in the '718 application. DWIPL **101** further includes a bulb **107**, disposed proximate to side **103A** and preferably generally opposed to probe **117**, containing a gas-fill **108** including a noble gas and a light emitter, which when receiving microwave energy at a predetermined operating frequency and intensity forms a plasma and emits light. As used herein, the term "ignition" means initial breakdown of atoms or molecules of the initially neutral gas-fill into ions. As used herein, the term "bulb" refers to an enclosure disposed substantially if not totally within a lamp chamber in a waveguide body, which either is a "bulb envelope," viz., an enclosure determined by a surrounding wall and a window covering the chamber aperture and hermetically sealed to the wall, or is a self-enclosed discrete bulb within the chamber. The term "bulb cavity," where used

herein, refers to the combination of a lamp chamber and a discrete bulb disposed within the chamber. Because the gas-fill is confined to a discrete bulb, a bulb cavity need not be hermetically sealed.

[0024] Source **115** provides microwave energy to waveguide **103** via probe **117**. The waveguide contains and guides the energy to an enclosed lamp chamber **105**, depending from side **103A** into body **104**, in which is disposed bulb **107**. This energy frees electrons from noble gas atoms, thereby creating a plasma. The free electrons excite the light emitter. De-excitation of the light emitter results in emission of light. As will become apparent, the DWIPL embodiments disclosed herein offer distinct advantages over the plasma lamps in the related art, such as an ability to produce brighter and spectrally more stable light, greater energy efficiency, smaller overall lamp sizes, and longer useful life spans.

[0025] The microwave source **115** in **FIG. 1** is shown schematically as solid state electronics; however other devices commonly known in the art operating in the 0.5 - 30 GHz range may also be used, including but not limited to klystrons and magnetrons. The preferred operating frequency range for source **115** is from about 500 MHz to about 10 GHz.

[0026] Depending upon the heat sensitivity of source **115**, the source may be thermally isolated from bulb **107**, which during operation typically reaches temperatures between about 700°C and

about 1000°C. Thermal isolation of bulb **107** from source **115** provides a benefit of avoiding degradation of the source due to heating. Additional thermal isolation of the source may be accomplished by any one of a number of methods commonly known in the art, including but not limited to using an insulating material or vacuum gap occupying an optional space **116** between the source **115** and waveguide **103**. If the space **116** is included, appropriate microwave probes are used to couple the source **115** to the waveguide **103**.

[0027] In **FIG. 1**, probe **117** that transports microwave energy from the source **115** to the waveguide **103** preferably is a coaxial probe. However, any one of several different types of microwave probes known in the art may be used, such as microstrip lines or fin line structures.

[0028] Due to mechanical and other considerations such as heat, vibration, aging and shock, when feeding microwave energy into the dielectric material, contact between the probe **117** and waveguide **103** preferably is maintained using a positive contact mechanism **121**. The mechanism provides a constant pressure by the probe on the waveguide to minimize the possibility that microwave energy will be reflected back through the probe rather than entering the waveguide. In providing constant pressure, the contact mechanism compensates for small dimensional changes in the probe and waveguide that may occur due to thermal heating or mechanical shock. Contact mechanism **121** may be a spring loaded device, such as illustrated in **FIG. 1**, a bellows type device, or any other device commonly known in the art that can sustain a

constant pressure for continuously and steadily transferring microwave energy.

[0029] When coupling probe **117** to waveguide **103**, intimate contact preferably is made by depositing a metallic material **123** directly on the waveguide at its point of contact with the probe. This material eliminates gaps that may disturb the coupling, and preferably includes gold, silver or platinum, although other conductive materials may be used. The material may be deposited using any one of several methods commonly known in the art, such as depositing the material as a liquid and then firing it in an oven to provide a solid contact.

[0030] In **FIG. 1**, waveguide **103** is in the shape of a rectangular prism. However, the waveguide may have a cylindrical prism shape, a sphere-like shape, or any other shape that can efficiently guide microwave energy from the probe **117** to the bulb **107**, including a complex, irregular shape whose resonant frequencies preferably are determined using electromagnetic theory simulation tools. The actual dimensions of the waveguide will vary depending upon the microwave operating frequency and the dielectric constant of the waveguide body **104**.

[0031] In one preferred embodiment, body **104** has a volume of approximately 12,500 mm^3 and a dielectric constant of approximately 9, and the operating frequency is approximately 2.4 GHz. Waveguide bodies of this scale are significantly smaller than the waveguides in the plasma lamps of the related art. Thus, waveguides according to the present invention represent a significant

advance over the related art because their smaller size allows them to be used in many applications where the smallest size achievable heretofore has precluded or made wholly impractical such use. By using materials with larger dielectric constants, even smaller sizes can be achieved. Besides the obvious advantages provided by smaller size, size reduction translates into higher power density and lower loss, thereby making lamp ignition easier.

[0032] Regardless of its shape and size, waveguide body **104** preferably includes a solid dielectric material having the following properties: (1) a dielectric constant greater than approximately 2; (2) a loss tangent less than approximately 0.01; (3) a thermal shock resistance quantified by a failure temperature greater than approximately 200°C; (4) a DC breakdown threshold greater than approximately 200 kilovolts/inch; (5) a coefficient of thermal expansion less than approximately 10^{-5}/°C; (6) a zero or slightly negative temperature coefficient of the dielectric constant; (7) stoichiometric stability over a temperature range of about -80°C to about 1000°C; and (8) a thermal conductivity of approximately 2 W/mK (watts per milliKelvin).

[0033] Certain ceramics, including alumina, zirconia, titanates and variations or combinations of these materials may satisfy many of the above preferences, and may be used because of their electrical and thermo-mechanical properties. Alternatively, the dielectric material may be a silicone oil. Preferably, body **104** has a substantial thermal mass which aids efficient distribution and dissipation of heat and provides thermal isolation between source **115** and bulb **107**.

[0034] Referring to **FIG. 2A**, a DWIPL **200** includes a waveguide **203** having a body **204** consisting essentially of a solid dielectric material, and a side **203A** with an enclosed lamp chamber **205** depending from side **203A** into body **204**. A bulb **207** is disposed within the chamber. DWIPL **200** further includes a microwave probe **209** generally opposed to chamber **205**. Preferably, bulb **207** is in the same plane as probe **209**, where the electric field of the microwave energy is at a maximum. Where more than one maximum of the electric field is present in waveguide **203**, the chamber and bulb are positioned at one maximum and the probe at another maximum. By placing the probe and bulb at field maxima, the amount of energy transferred into the bulb is maximized.

[0035] Referring to **FIG. 2B**, a DWIPL **220** includes a waveguide **223** having a body **224** with a main portion **224A** consisting essentially of a solid dielectric material. Body **224** further includes a convexly-shaped portion **224B** which protrudes outwardly from portion **224A** to form an enclosed lamp chamber **225**. As in DWIPL **200**, a bulb **227** disposed within chamber **225** is positioned generally opposed to a microwave probe **221**. In contrast to DWIPL **200**, bulb **227** may be positioned in a plane other than the plane of probe **221** where more than one maximum of the electric field is present in waveguide **223**.

[0036] Returning to **FIG. 1**, sides **103A, 103B, 103C, 103D** of waveguide **103**, with the

exception of those surfaces depending from side **103A** into body **104** which form lamp chamber **105**, are coated with a thin metallic coating **119** which reflects microwaves in the operating frequency range. The overall reflectivity of the coating determines the level of energy within the waveguide. The more energy that can be stored within the waveguide, the greater the efficiency of lamp **101**. Preferably, coating **119** also suppresses evanescent radiation leakage and significantly attenuates any stray microwave field(s).

[0037] Microwave leakage from chamber **105** is significantly attenuated by choosing the chamber dimensions to be significantly smaller than the wavelength(s) of the microwaves used to operate lamp **101**. For example, the length of the diagonal of a window sealing the chamber should be considerably less than half the microwave wavelength (in free space).

[0038] Still referring to **FIG. 1**, bulb **107** includes an outer wall **109** having an inner surface **110**, and a window **111**. Alternatively, the lamp chamber wall acts as the outer wall of the bulb. The components of bulb **107** preferably include at least one dielectric material, such as a ceramic or sapphire. In one embodiment, the ceramic in the bulb is the same as the material used in body **104**. Dielectric materials are preferred for the bulb **107** because the bulb preferably is surrounded by the body **104**, and the dielectric materials facilitate efficient coupling of microwave energy with the gas-fill **108** in the bulb.

[0039] In **FIG. 1**, outer wall **109** is coupled to window **111** using a seal **113**, thereby determining a bulb envelope **127** which contains the gas-fill **108**. The plasma-forming gas preferably is a noble gas. The light emitter preferably is a vapor formed of any one of a number of elements or compounds known in the art, such as sulfur, selenium, a compound containing sulfur or selenium, or a metal halide such as indium bromide (InBr).

[0040] To confine the gas-fill within the bulb envelope, the seal **113** preferably is a hermetic seal. Outer wall **109** preferably includes alumina because of its white color, temperature stability, low porosity, and coefficient of thermal expansion. However, other materials that provide one or more of these properties may be used. Preferably, outer wall **109** is contoured to maximize the amount of light reflected out of chamber **105** through window **111**. For instance, the outer wall may have a parabolic contour. However, other outer wall contours or configurations that facilitate directing light out through the window may be used.

[0041] Window **111** preferably includes sapphire for high light transmissivity and because its coefficient of thermal expansion matches well with that of alumina. Alternatively, other materials having similar light transmittance and thermal expansion properties may be used. Alternatively, window **111** includes a lens to collect the emitted light.

[0042] As referenced above, during operation bulb **107** may reach temperatures of up to about

1000°C. Under such conditions, body **104** acts as a heat sink for the bulb. By reducing the heat load and heat-induced stress on the various elements of DWIPL **101**, the lamp's useful life span can be increased beyond the life span of electrodeless lamps in the related art. As shown in **FIG. 1**, effective heat dissipation may be obtained by attaching a plurality of heat-sinking fins **125** to sides **103A, 103C** and **103D**. In DWIPL **220** (see **FIG. 2B**), lamp chamber **225** extends away from the main portion **224A** of body **224**, allowing heat to be removed efficiently by placing a plurality of fins **222** proximate to bulb **227**.

[0043] Alternatively, waveguide body **104** includes a dielectric, such as a titanate, which generally is unstable at high temperature. In such embodiments, the waveguide **103** preferably is shielded from the heat generated in bulb **107** by interposing a thermal barrier between the body and bulb. Alternatively, the outer wall **109** includes a material with low thermal conductivity, such as an NZP ($NaZr_2(PO_4)_3$) ceramic, which acts as a thermal barrier.

[0044] **FIGs. 3A** and **3B** illustrate a DWIPL **300** wherein a vacuum gap acts as a thermal barrier. As shown in **FIG. 3A**, DWIPL **300** includes a bulb envelope **313** disposed within a lamp chamber **315** which is separated from body **312** of a waveguide **311** by a vacuum gap **317** whose thickness is dependent upon microwave propagation characteristics and the material strengths of waveguide body **312** and bulb envelope **313**. The vacuum minimizes heat transfer between the bulb and waveguide.

[0045] FIG. 3B illustrates a magnified view of bulb envelope **313**, chamber **315** and vacuum gap **317**. The boundaries of gap **317** are formed by the waveguide **311**, a bulb envelope support **319**, and bulb envelope **313**. Support **319** is sealed to the waveguide and extends over the edges of chamber **315**. The support includes a material having high thermal conductivity, such as alumina, to help dissipate heat from the bulb.

[0046] Embedded in support **319** is an access seal **321** which maintains a vacuum within gap **317** when bulb envelope **313** is in place. Preferably, the bulb envelope **313** is supported by and hermetically sealed to support **319**. Once a vacuum is established in gap **317**, heat transfer between the bulb envelope and waveguide is substantially reduced.

[0047] Preferably, DWIPLs **101, 200, 220** and **300** operate at a microwave frequency in the range of about 0.5 to 10 GHz. The operating frequency is preselected so as to excite one or more resonant modes supported by the size and shape of the waveguide, thereby establishing one or more electric field maxima within the waveguide. When used as a resonant cavity, at least one dimension of the waveguide is preferably an integer number of half-wavelengths.

[0048] FIGs. 4A, 4B and **4C** schematically illustrate three DWIPLs **410, 420, 430**, each operating in a different resonant mode. It is to be understood that each of these figures represents

DWIPL **101**, DWIPL **200**, DWIPL **220** or DWIPL **300** operating in the respective resonant mode depicted. Referring to **FIG. 4A**, DWIPL **410** operates in a first resonant mode **411** where the length of one axis of a rectangular prism-shaped waveguide **417** is one-half the wavelength of the microwave energy used. In **FIG. 4B**, DWIPL **420** operates in a second resonant mode **421** where the length of one axis of a rectangular prism-shaped waveguide **427** equals the microwave wavelength. In **FIG. 4C**, DWIPL **430** operates in a third resonant mode **431** where the length of one axis of a rectangular prism-shaped waveguide **437** is three-halves the microwave wavelength. DWIPL **430** includes first and second microwave probes **433, 434** which supply energy to the waveguide. The probes may be coupled to a single microwave source or individually to separate sources. DWIPLs **410, 420, 430** further include, respectively, a bulb cavity **415, 425, 435**.

[0049] In DWIPLs **410, 420, 430**, bulb cavities **415, 425, 435**, respectively, and probes **413, 423**, and **(433, 434)**, respectively, are preferably positioned with respect to waveguides **417, 427, 437**, respectively, at locations where the electric fields are at an operational maximum. However, the bulb cavity and probe(s) do not necessarily have to lie in the same plane.

[0050] **FIG. 4D** schematically illustrates a DWIPL **440** wherein a single microwave probe **443** provides energy to a waveguide **447** having first and second bulb cavities **445, 446**, each positioned with respect to the waveguide at locations where the electric field is at a maximum.

It is to be understood that **FIG. 4D** represents DWIPL **101**, DWIPL **200**, DWIPL **220** or DWIPL **300** operating in the resonant mode depicted, but with the DWIPL modified to include two bulb cavities.

[0051] **FIGs. 5A**, **5B** and **5C** schematically illustrate three DWIPLs **510**, **520**, **530** each having a cylindrical prism-shaped waveguide **517**, **527**, **537**, respectively, and operating in a different resonant mode. It is to be understood that each of these figures represents DWIPL **101**, DWIPL **200**, DWIPL **220** or DWIPL **300** operating in the respective resonant mode depicted, but with the DWIPL modified to have a cylindrical waveguide. In each DWIPL, the height of the cylinder is less than its diameter, and the diameter is close to an integer multiple of the lowest order half-wavelength that can resonate within the waveguide. Placing these dimensional constraints on the cylinder results in the lowest resonant mode being independent of cylinder height so that the cylinder diameter dictates the fundamental mode of the energy within the waveguide. Cylinder height can thus be optimized for other requirements such as size and heat dissipation. In **FIG. 5A**, a microwave probe **513** is positioned directly opposed to bulb cavity **515** where the zeroeth order Bessel mode **511** is a maximum. In **FIG. 5B**, cylindrical waveguide **527** has a diameter close to one wavelength long, so that the first order Bessel mode **521** is excited. Probe **523** is positioned at the field maximum and is diagonally opposed to bulb cavity **525**. In **FIG. 5C**, cylindrical waveguide **537** has a diameter close to three half-wavelengths long so that there are two electric field maxima at which are positioned probes **533**, **534** which provide energy to the

waveguide. Bulb cavity **535** is disposed symmetrically between the two probes. Generally, in a DWIPL having a cylinder-shaped waveguide the bulb cavity and probe(s) are preferably positioned with respect to the waveguide at locations where the electric field is a maximum.

[0052] A dielectric waveguide provides several distinct advantages. Firstly, as discussed above, the waveguide body can be used to dissipate heat generated in the bulb. Secondly, higher power densities can be achieved within a dielectric waveguide than are possible in plasma lamps with air cavities such as those in present use. Depending on the dielectric constant of the material used for the waveguide body, the energy density of a dielectric waveguide will be somewhat or substantially greater than the energy density in an air cavity waveguide of similiar dimensions in a plasma lamp of the related art.

[0053] Referring again to **FIG. 1**, high resonant energy within waveguide **103** of DWIPL **101**, corresponding to a high Q-value in the waveguide (where Q is the ratio of the operating frequency to the frequency width of the resonance), results in high evanescent leakage of microwave energy into chamber **105**. High leakage into the chamber leads to quasi-static breakdown of the noble gas within envelope **127**, thereby generating the first free electrons. The oscillating energy of the free electrons scales as $I\lambda^2$, where I is the circulating intensity of the microwave energy and λ is the wavelength. Thus, the higher the microwave energy, the greater is the oscillating energy of the free electrons. By making the oscillating energy greater than the

ionization potential of the gas, electron-neutral collisions result in efficient build-up of plasma density.

[0054] Once a plasma is formed in DWIPL **101** and the incoming power is absorbed, the waveguide's Q-value drops due to the conductivity and absorption properties of the plasma. The drop in Q-value is generally due to a change in the impedance of the waveguide. After plasma formation, the presence of the plasma in the chamber makes the chamber absorptive to the resonant energy, thus changing the waveguide impedance. This change in impedance is effectively a reduction in the overall reflectivity of the waveguide. By matching the reflectivity of the probe to be close to the reduced reflectivity of the waveguide, a relatively low net reflection back into the energy source is realized.

[0055] Much of the energy absorbed by the plasma eventually appears as heat such that the bulb temperature may approach 1000°C. When the waveguide is also used as a heat sink, as previously described, the dimensions of the waveguide may change due to thermal expansion. If the waveguide expands, the microwave frequency that will resonate within the waveguide changes and resonance is lost. In order for resonance to be maintained, the waveguide must have at least one dimension equal to an integer multiple of the half-wavelength of the microwaves being generated by source **115**.

[0056] A DWIPL embodiment that compensates for such dimensional changes includes a waveguide having a body consisting essentially of a solid dielectric material with a temperature coefficient for its refractive index that is approximately equal and opposite in sign to its coefficient of thermal expansion. Dimensional changes due to thermal heating are offset by a change in refractive index, thus decreasing the possibility that resonance will be interrupted. Such materials include titanates. Alternatively, dimensional changes due to heating may be compensated for by tapering the walls of the waveguide.

[0057] **FIG. 6** schematically shows a DWIPL **610** operated in a dielectric resonant oscillator mode wherein first and second microwave probes **613**, **615** are coupled between a dielectric waveguide **611**, which may be of any shape previously discussed, and a microwave energy source **617**. Source **617** is preferably broadband with a high gain and high output power, and is capable of driving the plasma to emission. DWIPL **610** further includes a bulb cavity **619**.

[0058] Probe **613** generally operates as described for the other embodiments disclosed herein. Probe **615** probes the waveguide **611** to instantaneously sample the field (including amplitude and phase information contained therein), and provides the sampled field information via a feedback means **612** to an input **617A** of energy source **617** or to a separate amplifier. In probing the waveguide, probe **615** also preferably acts to filter out stray frequencies, leaving only the resonant frequency within the waveguide. Preferably, probes **613**, **615** and bulb cavity **619** are

each positioned with respect to waveguide **611** at locations where the electric field is at a maximum. Using the sampling information provided by probe **615**, the energy source **617** amplifies the resonant energy within the waveguide. The source thereby adjusts its output frequency to dynamically maintain one or more resonant modes in the waveguide. The complete configuration thus forms a resonant oscillator. In this manner, automatic compensation may be realized for frequency shifts due to plasma formation and changes in waveguide dimensions and dielectric constant due to thermal effects, enabling continuous operation of the lamp.

[0059] The dielectric resonant oscillator mode also enables DWIPL **610** to have an immediate re-strike (i.e., re-ignition) capability after being turned off. As previously discussed, the resonant frequency of the waveguide may change due to thermal expansion and/or changes in the dielectric constant caused by heat generated during operation. Furthermore, the resonant frequency depends upon the state of the plasma. When DWIPL **610** is shut down, the light-emitting plasma extinguishes and heat is dissipated resulting in changes in the resonant frequency of the waveguide.

[0060] However, as indicated above, in the resonant oscillator mode the energy source **617** automatically compensates for changes in the resonant frequency of the waveguide **611**. Therefore, regardless of the startup characteristics of the waveguide, and providing that energy source **617** has the requisite bandwidth, the energy source will automatically compensate to

achieve resonance within the waveguide. Thus, the energy source immediately provides power to the DWIPL at the optimum plasma-forming frequency.

[0061] While several embodiments for carrying out the invention have been shown and described, it will be apparent to those skilled in the art that additional modifications are possible without departing from the inventive concepts detailed herein. It is to be understood, therefore, there is no intention to limit the invention to the particular embodiments disclosed. On the contrary, it is intended that the invention cover all modifications, equivalences and alternative constructions falling within the spirit and scope of the invention as expressed in the appended claims.